

## Context and non-locality

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*Publication date:*  
1987

*Document Version*  
Publisher's PDF, also known as Version of record

*Citation for published version (APA):*  
Christiansen, P. V. (1987). *Context and non-locality*. Paper presented at Symposium af the Foundations of Modern Physics, Joensuu, Finland.

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## Context and Non-Locality – A Peircean Approach.

Paper presented at the  
Symposium on the Foundations of Modern Physics  
The Copenhagen Interpretation  
60 Years after the Como Lecture.  
Joensuu, Finland, 6 – 8 august 1987.

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## TEKSTER fra

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FUNKTIONER I UNDERVISNING, FORSKNING OG ANVENDELSER

IMFUFA, Roskilde Universitetscenter, Postbox 260, 4000 Roskilde

Context and Non-Locality - A Peircean Approach.

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IMFUFA tekst nr. 144/87      29 pages

ISSN 0106-6242

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#### ABSTRACT

The aim of the Copenhagen interpretation of quantum mechanics is to provide a semantics for the symbols of the mathematical formalism. Niels Bohr's early philosophy which has a direct connection with his later ideas of complementarity is inspired both by danish existentialism and american pragmatism. The founder of pragmatism, C.S.Peirce, was, however, not known to Bohr, and Peirce's complete classification of non-linguistic signs has never been considered in connection with the Copenhagen-semantics, which is therefore in certain respects incomplete. In this paper it will be argued that Peirce's semiotic is a natural basis for quantum-semantics and that his "synechistic" concept of local realism can be tested experimentally. This opens a possibility of avoiding some of the extravagant ontological interpretations that have emerged in later years in consequence of the experimentally observed violations of Bell's inequalities.

For the edition of this paper as an IMFUFA-text two appendices have been added given pictorial derivations of some of the more formalistic points. Appendix A considers Peirce's logic of relations and his triadic doctrine of categories for the purpose of a general classification of signs. Appendix B discusses the derivation of Bell's inequalities from the classical calculus of logic without introducing local hidden variables.

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The Copenhagen interpretation is often regarded as identical with the pure mathematical formalism and many textbooks nowadays neglect the epistemological questions that were so important before the formalism got its final shape in the late twenties. This neglect of philosophical questions may be partly due to Bohrs attitude in his later years where he emphasized that ordinary language is insufficient and even misleading and that it must be replaced by the mathematical formalism. This attitude seems to have been connected with scepticism towards philosophy in general, at least it has been interpreted in this way by philosophers of a somewhat positivistic inclination who tend to disregard the important role of philosophy as inspirator for new developments in physics<sup>1</sup>.

However, in his younger years Bohr was very engaged in philosophical speculations, and there is a strong historical evidence<sup>2</sup> indicating that the philosophy of complementarity was evolved long before quantum mechanics and is influenced by several streams of philosophy as focused by Bohrs philosophical teacher Harald Høffding. Max Jammer<sup>3</sup> has pointed out the influence from the danish existentialist Søren Kierkegaard as important for an understanding of Bohr's ideas of the quantum jumps, and Witt-Hansen<sup>4</sup> has drawn attention to the continuity-thinking of Leibniz, as mediated by Høffding, which seems closely connected with Bohr's correspondence-principle.

In this paper we shall look upon the influence from american pragmatism as exposed by William James (and Høffding) and the regrettable lack of influence from its originator, Charles S. Peirce, who was unknown to Bohr and has been neglected by and large in this century, until quite recently. The author's interest in these questions of history of philosophical influences on quantum mechanics is

not so much connected to historical philosophy as to the conviction that the difficulties of interpretation that confront quantum mechanics nowadays, especially after the Aspect-experiments, are real and serious and concerning semantics, not the mathematical formalism.

Many weird ontologies, involving backwards causality, splitting universes, telepathic synchronicity, or just a plain old-fashioned pre-established non-local harmony are invoked in these years in order to explain the observed violations of Bell's inequalities. The author believes that such ontologies, although some of them are interesting and may be valuable in other contexts, have nothing to do with quantum mechanics, which is a simple and logical theory with the very limited scope of explaining elementary phenomena of the atomic world in a consistent way.

It will be argued that, according to Peirce, a local realism is not identical with the existence of local hidden variables and therefore not automatically leading to Bell's inequalities. The Aspect experiments are convincing proofs of the validity of the quantum formalism under the circumstances set in the laboratory, and, although some weak loopholes remain, they may be regarded as counterproofs of theories of local hidden variables. This does not mean, however, that the concept of local realism, or Einstein-separability, has been disproved. The "synechistic" sort of local realism, as proposed by Peirce, has never been subjected to an experimental test, although it could easily be by a small alteration that would bring the experiments in closer relation to the thought experiment proposed by Einstein, Podolski and Rosen. Until now the experiments have just pointed to the need for a semiotic reconsideration of the quantum formalism but cannot be taken as evidence for the validity of extravagant ontologies.

## HØFFDING, AND THE YEARS OF ECLIPTICA.

Niels Bohr began the study of physics at the Copenhagen University in the year 1903. At that time all students were initiated to the academic world through an introductory course in "propedeutic philosophy". The professor of philosophy, Harald Høffding, was an old friend of Bohr's father and had been a frequent guest in their home where lively discussions of science, philosophy and politics took place. Niels and his brother Harald were thus well prepared to take part in a continuation of the cross-cultural spirit of Copenhagen from "the golden age" in the 19th century. The fertile ground created by such giants as N.F.S.Grundtvig and S.Kierkegaard was still blossoming at the turn of the century with a new poetic realism and impressionism in the literature and a cultural radicalism in philosophy and politics, opposed to the dictatorial conservative Estrup government and with Høffding and the brothers Brandes as leading figures.

In the autumn of 1904 Høffding made a journey to USA and England. After having returned full of new ideas he started a series of philosophical colloquia at the university. A group of 12 students attending these colloquia, among them Niels and Harald Bohr, formed a circle called Ecliptica with the purpose of further discussions of the philosophical topics that Høffding called their attention to. We have no detailed written reports of the discussions at these meetings, but we know that the atmosphere was stimulating, although heavily polluted with tobacco smoke. Not less than three internationally recognized "Copenhagen schools" have emerged from this small circle, viz. Niels Bohr's in physics, Edgar Rubin's in

psychology, and Viggo Brøndal's (and Louis Hjelmslev's) structural linguistics.

One of the Copenhagen philosophers of the 19th century that must have played a great role in the discussions is Søren Kierkegaard, a highly religious thinker who exhausted himself in violent attacks against the established church. Høffding was an expert in Kierkegaard's philosophy and considered his existentialistic writings on the choice and "the qualitative jump" to be of importance far outside theology, in the general logic of concepts and psychology. Kierkegaard was very critical against Hegel's dialectical philosophy, especially the thesis of quantity turning over into quality. In several books from around 1845, e.g. "Begrebet Angest" (The Concept of Dread) he analyzes the free choice as something that cannot be reduced or explained away by quantitative means. The choice is a qualitative jump confronting the subject with a vacuum that creates dizziness, nausea and dread. Kierkegaard employs a peculiar circular or "bootstrapping" logic in describing the jump, which is said to be a choice between possibilities that are presupposed or preset by the jump. Høffding's first series of colloquia in the spring of 1905 were discussions of the concept of free will and Kierkegaard's ideas must have had a central place. Niels Bohr has in several letters from 1909 reported how his own readings of Kierkegaard made a deep impression on him, and it is rather easy to see how many of his more cryptic remarks on complementarity bear a close resemblance to Kierkegaard's formulations.

Another important influence on Bohr's thinking in the early years of Ecliptica comes from America, viz. William James. During his stay in USA in the autumn 1904 Høffding had been the guest of William James and in his memoirs<sup>5</sup> he describes what great inspiration the contact with James had



been to him. In an interview given to Thomas Kuhn and Aage Petersen<sup>1</sup> the day before his death Bohr tells that he read William James in his young years and that James' description of "the stream of consciousness" had made a lasting impression on him.

Besides being a pioneer of depth-psychology James is also considered the founder of the pragmatic school of philosophy. This school is founded on the so called pragmatic criterion of meaning which is closely related to Bohr's semantic thesis that the meaning of the quantum mechanical symbols is set by the experimental context. James himself, however, did not consider himself the inventor of pragmatism but pointed to his old friend Charles Sanders Peirce who had first formulated the pragmatic criterion of meaning in a paper "How to make our ideas clear" from 1878. There is no indication that Høffding or Bohr knew anything of Peirce's philosophy, but there is an indirect connection so far as James' influence is important and is inspired by a life-long acquaintance with Peirce.

Another indication of an indirect connection from Peirce to Bohr is found in the fact that Høffding after his stay in America went to England in the late autumn of 1904 where he stayed as a guest in the house of another of Peirce's close friends, the Lady Victoria Welby. A great part of Peirce's general theory of signs, semiotic, is evolved in letters to Lady Welby who herself had made original contributions to the theory of semantics. Peirce is known to have warned Lady Welby "perhaps you are in danger of falling into some error in consequence of limiting your studies so much to language"<sup>6</sup>. Unfortunately, this warning never went through to Bohr who remained "suspended in language"<sup>7</sup>.

## WHAT WENT WRONG IN COPENHAGEN?

In his discussions with Einstein at the Solvay meetings 1927-30 Bohr maintained the pragmatic attitude that the meaning of the symbols for position and momentum is set by the apparatus of measurement which itself is subject to the fluctuations described in Heisenberg's uncertainty relations. These fluctuations are thus inherent in the quantum mechanical semiosis, and we are not allowed to say that some "true" values are "disturbed" by the measurement process, because true values are created by the measurement and must not in general be assumed to exist by themselves in nature. This is all very much in accordance with Peirce's epistemology as described in an article from 1892<sup>8</sup>. Peirce would also agree with Bohr in the view that physicists must allow God the freedom to play dice. This view, that chance is a genuine and irreducible factor in the physical universe was advocated as "tychism" in the above mentioned article.

Einstein tried at the Solvay meetings to demonstrate that quantum mechanics was inconsistent, i.e. that it contained an intrinsic logical flaw that would turn up in situations clearly within the scope of the theory. However, after 1930 he seems to have been convinced of its consistency within a limited field. His next attack, in 1935 with Podolski and Rosen<sup>9</sup>, is an attempt to demonstrate the incompleteness of the theory, i.e. that there are real situations where the theory cannot be applied or where it would lead to false predictions if one tried to apply it. In the light of Gödel's incompleteness theorem from 1931 the accusation of being incomplete would not seem so serious, because in mathematics this property is a necessary consequence of the consistency of the theory. Probably Einstein thought that the situation was analogous in

physics, although he did not refer to Gödel's theorem. He had at that time just obtained a permanent position in Princeton and was joined by Gödel shortly afterwards.

In Copenhagen, however, the distinction between consistency and completeness was hardly noticed. L. Rosenfeld who took dictations from Bohr in his reply to Einstein, Podolski and Rosen (EPR) has in the memorial volume "Niels Bohr"<sup>10</sup> given a vivid report on the efforts which leaves the impression that Bohr was trying to live up to his image as the great champion of the fights with Einstein rather than trying to understand in what respects the EPR paper presented a new viewpoint. Consider, for example the following quotation from Rosenfeld's report (my translation from danish):

"Day after day, week after week the whole argumentation was patiently investigated by means of simpler and more transparent examples. Einstein's problem was reshaped and its solution formulated again with such precision and clarity that the weakness in the reasoning of the critics became evident and their whole argumentation, in spite of all its fake spirituality, was shattered to pieces. "They do it nicely," was Bohr's comment, "but what counts is to do it correctly"."

The myth about the "precision and clarity" of Bohr's reply to EPR<sup>11</sup> does not stand for a closer scrutiny. Einstein never understood it and consequently the debate came to a stalemate. J.S.Bell has declared<sup>12</sup> that Bohr's reply is "totally obscure" and similar but more vague declarations of uneasiness have been issued by Dirac and Feynmann. Even Bohr himself had to admit when he reread the paper in 1949 that he "strongly felt the inadequacy of expression"<sup>13</sup>. It is not the entire article that is obscure but a definite place that Bohr and Bell are referring to.

In the first part of the article Bohr pursues the line of argumentation that had proven so successful in the Solvay discussions:

" The finite interaction between the object and the measuring agencies conditioned by the very existence of the quantum of action entails - because of the impossibility of controlling the reaction of the object on the measuring instruments if these are to serve their purpose - the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality."

This is still a physical way of reasoning and it does not exclude a realistic attitude but just a semiotically unreflected sort of realism that would ascribe definite numerical values to quantities of the undisturbed reality. There is a strong resemblance between the Bohr-quotation above and the way Peirce argues against "the doctrine of necessity" in 1892<sup>8</sup> (but of course Peirce does not mention the quantum of action):

"Try to verify any law of nature and you will find that the more precise your observations, the more certain they will be to show irregular departures from the law. We are accustomed to ascribe these, and I do not say wrongly, to errors of observation; yet we cannot usually account for such errors in any antecedently probable way. Trace their causes back far enough, and you will be forced to admit they are always due to arbitrary determination, or chance."

In connection with this view on observations in general Peirce criticizes "the necessitarian position - that certain continuous quantities have exact values" and concludes that "any statement to the effect that a certain continuous

quantity has an exact value, if well-founded at all, must be founded on something other than observation." In short: Bohr and Peirce agree that the analysis of the measurement process calls for a semiotic reconsideration of our notions of the undisturbed physical reality, but Bohr's argument is ontological, based on the existence of the quantum of action, whereas Peirce's argument is epistemological and based on our inability to account for errors of measurements "in any antecedently probable way". One may conjecture that Peirce, had he known about the quantum of action, would have supported Bohr's argument wholeheartedly.

However, in the later part of Bohr's reply to EPR there is a sudden turning away from the, still potentially realistic, attitude in the first quotation. This is the exact place where the article becomes obscure (both according to Bell and Bohr). In discussing the EPR thought experiment where a measurement on one particle can be said to affect the state of another particle Bohr writes:

"Of course there is in a case like that just considered no question of a mechanical disturbance of the system under investigation during the last critical stage of the measurement procedure. But even at this stage there is essentially the question of an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system ."

This is almost certainly a place where Peirce would have objected, because Bohr tries to circumvent both realism (anti-nominalism) and synechism, i.e. the conception that signs exist outside the subjective mind and propagate through a continuum.

It is not clear what connection there could be between the "finite interaction" in the first Bohr-quotation and the

"very conditions" in the second. When we make a measurement on particle 1 we have a free choice of measuring one or the other of two complementary properties of this particle, e.g. position or momentum. The choice between the two different ways of interacting with particle 1 according to Bohr prohibits the use of the EPR-term "the same reality" for particle 2, even though this particle is not affected by any mechanical disturbance, and this is because quantum mechanics forces us to regard the whole phenomenon of preparation and measurement as possessing an "individuality completely foreign to classical physics". The "very conditions" in the second quotation thus seems to be the formalism of quantum mechanics associated with the philosophy of complementarity, and Bohr is trying to persuade the reader to accept that quantum mechanics defines how the term "physical reality" may be correctly used. This is of course difficult to accept from a realistic standpoint: when the question is whether the quantum mechanical description of physical reality is complete, then the answer that quantum mechanics itself defines what "physical reality" is looks like a philosophical shortcircuit or cheating in the game of debate.

Apart from breaking with realism, the introduction of the "very conditions" also breaks with the locality principle, or synechism. When we measure one or the other of the two complementary properties of particle 1 without disturbing particle 2 then it is true that quantum mechanics gives an unambiguous prediction for the future behavior of particle 2, viz. a wave function corresponding to a pure state of that particle. The "finite interaction" is in this case only involving particle 1, but it produces via the "very conditions" a change of state of particle 2. Bohr seems to forget that we still have the possibility of making

an independent measurement on particle 2 and that this would amount to a test of the formalism that can be performed whether one accepts the influence via the "very conditions" or not. What about the "finite interaction" with particle 2 that would be introduced by such a second measurement? Can we be sure that it doesn't produce a conflict with the "very conditions" if the two measurements really are physically independent ? These questions are unanswered in Bohr's article.

According to the orthodox Copenhagen interpretation (after 1935) one is really not allowed to ask such questions. Rosenfeld, as the guardian of the orthodoxy, states<sup>10</sup> that "the refusal of Einstein's criticism does not add any new element to the concept of complementarity". The rest is silence in Copenhagen. Attempts to formulate a realistic concept of the quantum world have been met with cryptic formulations stressing both that we are suspended in language, that the language is inadequate, and that our problem is to use the language correctly, which in most cases mean to abstain from the use of words and stick to the mathematical formalism, or to quote Bohr directly.

The author believes that the orthodoxy after 1935 is due to the fact that nobody (including Bohr himself) ever understood what the "very conditions" are. Something went wrong in Copenhagen in the very moment they were introduced. Until then the Copenhagen interpretation had pursued the reasonable goal of creating a "minimal semantics" as v. Weizsäcker states it, but afterwards even that task became impossible, because the "very conditions" create the illusion that the mathematical formalism makes up reality instead of describing it. A reconstruction of the original goal is very much needed nowadays, because the experimental violation of Bell's inequalities has created confusion.

## THE IRREDUCIBLE SIGN RELATION.

Following now the line of thought that the missing link in the minimal semantics of the Copenhagen interpretation is

1) a way to include the concept of non-linguistic signs of an undisturbed physical reality in the formalism, and

2) a description of conditions for their transformation to symbolic results of measurements,

we shall see how this may be done with the use of Peirce's general theory of signs, semiotic.

The first part of this program is in fact already achieved by Dirac with his introduction of the "kets" and the "bras", the concept of a state vector without reference to representation. With Peirce's terminology the ket is an example of a "degenerate" type of sign called an index and the representation is an interpretant which in combination with the index creates a non-degenerate sign, a symbol (the bra-ket).

The second part amounts to a proper theory of measurement, and this is not easily achieved, but one may hope that Peirce's idea of continuity and connectedness of sign relations, synechism, which were first expressed in a paper from 1892<sup>14</sup>, may add some simple criteria of connectedness as a necessary condition for a measurement apparatus to constitute an interpretant in a quantum-semiotic sign relation. At least this consideration points to the relevance of the connectedness of Aspect's equipment, the use of coincidence counters, to the contextuality of the measured polarizations, i.e. the non-locality exhibited by the violation of Bell's inequalities.

The application of Peirce's ideas to quantum mechanics of course requires some reshaping of concepts and cannot be



totally faithful to the original formulations. This is, however, not as bad as it may sound. Peirce, unlike Hegel, never created a completed system, and his aim was to develop scientific methods that could be applied by future researchers in an unending development. His own development of semiotic is a good example, it is easy to find contradicting statements in his writings, but his ideas are continually gaining in integrity and generality, and from about 1885 to his death in 1914 they seem free of contradictions. It is not necessary to read everything he wrote in order to use his ideas (which would be impossible, as he wrote about 80.000 pages), a few hints are sufficient in order to grasp the method, and from there one may proceed according to need of new development. The best starting point is the logic of relations and the triadic doctrine of categories. These concepts lead in a rigorous way to hierarchical systems of sign-classification that very soon become general enough to encompass all conceivable types of signs. A very useful classification based on a twofold application of the triadic categories (with some "selection rules") gives ten classes of signs<sup>15</sup>. This is already too much for our purpose; as long as we are mainly interested in the way the sign refers to the object a single trichotomy is sufficient.

Peirce's triadic doctrine of categories is based on the observation that a network of relations in more than one dimension requires at least triadic relations. On the other hand it can be shown that relations of order higher than three always can be reduced to triadic relations. A sign is defined as a genuine triadic relation involving

1. A primary sign or sign vehicle.
2. An object.
3. An interpretant.

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APPENDIX A.  
PEIRCE'S CLASSES OF SIGNS.

Peirce's semiotic is based on the logic of relations. In fig. 1 we look upon some of the most important observations in this discipline using a diagrammatic method known as bond graphs, where the relations are depicted as nodes and the constituent signs as branches of a network.

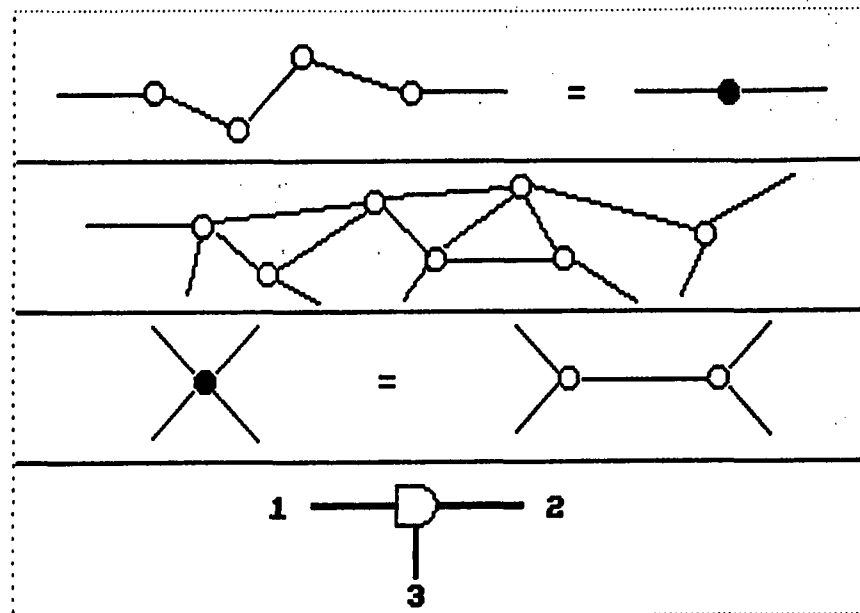


Fig. 1 . Bond graphs illustrating logic of relations.

Reading the figure from the top, the first illustration shows that a combination of dyadic relations, i.e. relations between two signs always lead to a new dyadic relation. These relations belong to a one-dimensional logic, but are not sufficient to build a general network. The next illustration from above shows that a network in more than one dimension has to include triadic relations or higher, corresponding to nodes connecting at least three branches.

The third illustration shows that relations of higher order than three always can be reduced to triadic relations. Finally the last illustration shows an icon of a prototype of a genuine triadic, asymmetric relation, the sign relation. Although we say that relations are relations between signs the logic of Peirce states that a sign is a relation. The two concepts, sign and relation, define each other, just like, e.g. part and whole.

The sign relation connecting 1. The primary sign, 2. The object, and 3. The interpretant gives rise to the three ontological categories, as described in the text, p. 16. In Fig. 2 the three factors of the sign relation are shown as the three axes of a coordinate system, and on each axis three points are marked, corresponding to the three ontological categories, firstness nearest to the origin.

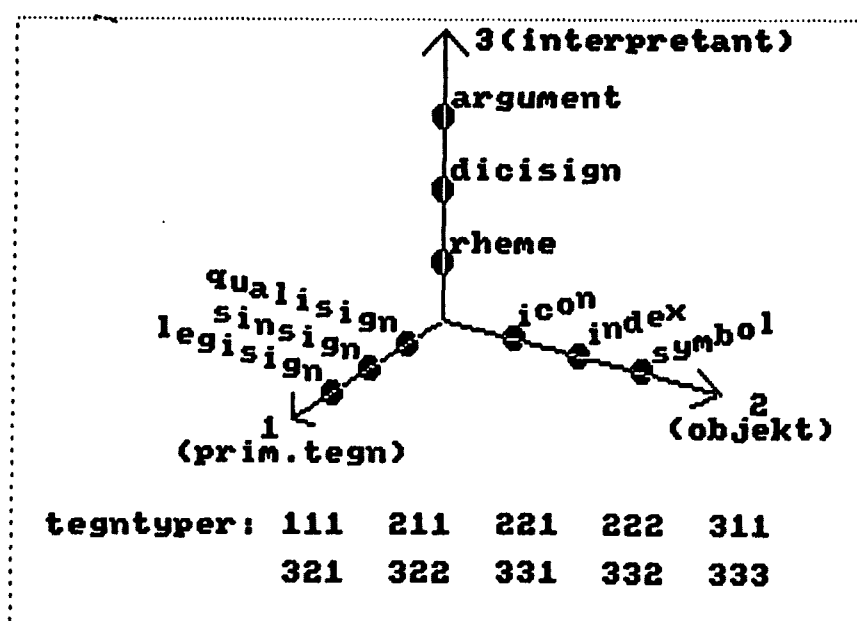


Fig. 2 . The classification of signs obtained by applying the ontological trichotomy to each of the three factors of the sign relation.

For the primary sign we get the three categories 1. qualisign, i.e. a pure quality (like the color red), 2. sinsign, a definite thing (like a particular red banner), and 3. legisign, a sign as representing a general class (like the banner of a trade union). For the object reference the trichotomy gives 1. icons, 2. indices, and 3. symbols, as discussed in the text, p. 16, and for the interpretant we get 1. rheme, or term, 2. dicisign, or proposition, and 3. argument.

These three tricotomies can be combined in 27 ways and all these possibilities can be depicted as points in 3-space. However, not all these 27 combinations correspond to legitimate sign-classes. There is a simple selection rule that may be formulated as follows:<sup>15</sup>

No lower order trichotomy can be applied to a lower place in the sign relation .

This means that an argument must be a symbolic legisign, a dicisign may be a symbolic legisign or an indexical legisign or an indexical sinsign, whereas a rheme may be a symbolic legisign, an indexical legisign, an indexical sinsign, an iconical legisign, an iconical sinsign or an iconical qualisign. All together there are ten classes of signs.

The reason why the selection rule is valid can be seen with a few simple examples: A symbol that refers to an object by some convention presupposes that the primary sign is considered as representing a general class, a legisign, e.g. in order to consider a red banner as a symbol of socialism we must know that such banners are used by trade unions for demonstrations on the first of may. In order to see the indexical reference of a banner to a particular trade union we must at least recognize it as a particular thing, a sinsign, and not just as "something red".

In quantum semiotic the most important trichotomy regards the object reference. A full, non-degenerate sign relation is needed in order to give birth to a symbol. The bonds in the sign relation of quantum semiotic must be regarded as interaction bonds of a concrete physical nature. Each bond connects two physical systems and describes an elementary interaction, system 1 acts on system 2 which acts back on system 1. In classical physics an interaction bond can be described with two symbolic variables, e.g. current and voltage, or velocity and force, such that the product of these variables gives the energy transfer per second, but in quantum mechanics no symbolic representation of these variables exist, because symbols presuppose a full sign relation of interaction bonds. The system theoretic description of the irreducible sign relation (p. 17) is illustrated on fig. 3.

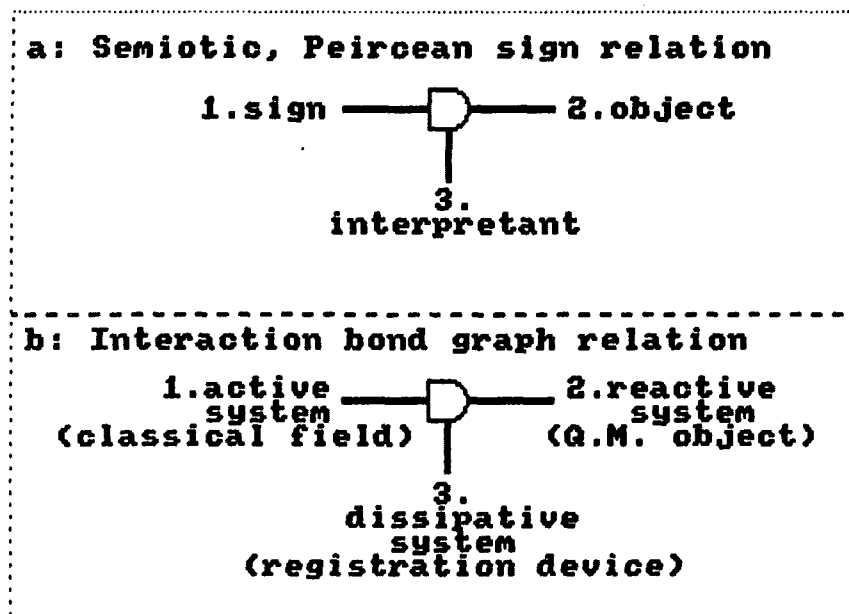


Fig. 3 . The sign relation, as described by Peirce, and in quantum semiotic.

APPENDIX B.  
THE BELL - SANTOS INEQUALITIES.

The classical calculus of logic assumes that it is possible for arbitrary propositions,  $a$  and  $b$ , to form negations,  $\neg a$ ,  $\neg b$ , conjunctions,  $a \wedge b$ , and disjunctions,  $a \vee b$  according to the rules:

$$\neg(a \wedge b) = \neg a \vee \neg b ; \neg(a \vee b) = \neg a \wedge \neg b \quad (B1)$$

$$a \wedge (b \vee c) = (a \wedge b) \vee (a \wedge c) ; a \vee (b \wedge c) = (a \vee b) \wedge (a \vee c) \quad (B2)$$

so that the operations of conjunction and disjunction correspond to the forming of intersections, respectively unions of sets. Truth values of the propositions may then be generalized to probabilities,  $p(a)$ , in accordance with Kolmogorov's axioms, so that

$$p(\neg a) = 1 - p(a) \quad (B3)$$

$$p(a \vee b) = p(a) + p(b) - p(a \wedge b) \quad (B4)$$

These rules assume an absence of context, i.e. that the probability of a certain property,  $a$ , does not depend on whether another property,  $b$ , is being measured simultaneously. In quantum mechanics this assumption can only be satisfied for a set of mutually compatible properties, described by commuting operators. For a single particle this condition will be rather natural, because a proposition like  $a \wedge b$  will be meaningless for complementary properties, like spin- $x$  and spin- $y$ , unless the experimental context is included in the propositions. For a two-particle system, however, we may find a set of properties,  $a_1, b_1, -$



for particle 1, each of which being compatible with every one of a set of properties,  $a_2, b_2$ , - for particle 2, so that propositions like  $a_1 \wedge b_2$  are perfectly meaningful, regardless of context.

For such a system it has been shown by E. Santos<sup>21</sup> that the rules of classical logic, (B1) - (B4), lead to the following inequalities:

$$0 \leq S(a_1, a_2) + S(a_1, b_2) + S(b_1, a_2) - S(b_1, b_2) \leq 2; \quad (B5)$$

where  $S$  is the "measure of separation":

$$S(a, b) = p(a) + p(b) - 2p(a \wedge b). \quad (B6)$$

Only the left inequality of (B5) is derived in Santos' paper, but the right one follows from the same formalism. Using the method of Venn-diagrams, in fig. 4 the measure of separation  $S(a_1, a_2)$  is represented by the shaded areas.

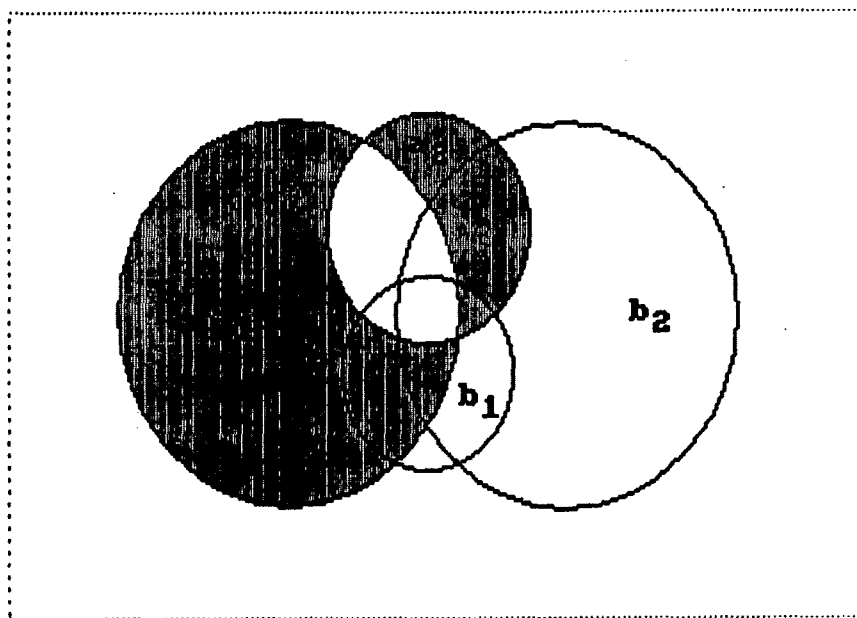


Fig. 4 Venn-diagram showing  $S(a_1, a_2)$  as shaded area.

When we as in (B5) add three of the four separation measures combining a property of particle 1 with one of particle 2 and subtract the fourth we get the Venn-diagram of fig. 5. In this case all the shaded areas are counted twice, and as the total measure is unity we get the inequality (B5).

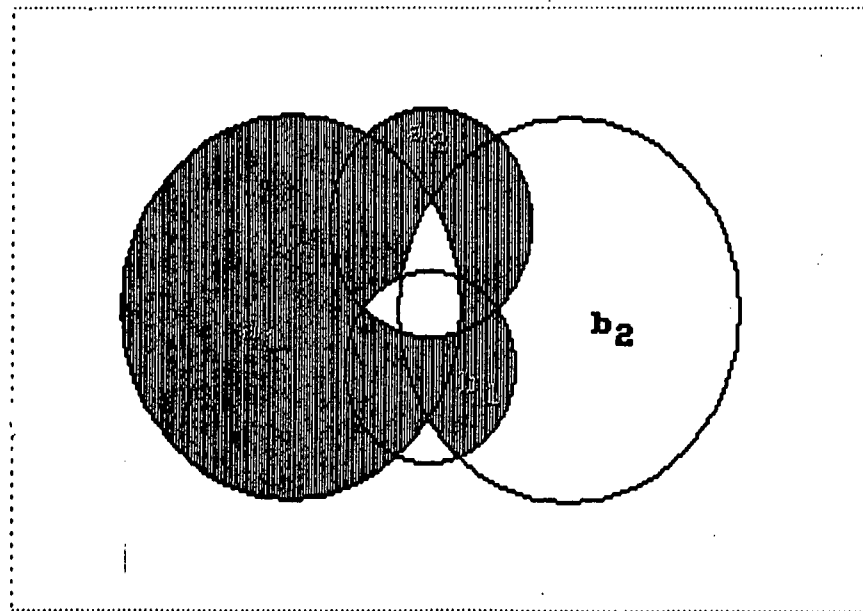


Fig. 5 . Venn-diagram illustrating the derivation of Santos' inequality (B5).

The use of Venn-diagrams for logical derivations presupposes the validity of the rules (B1) - (B4) so strictly speaking the diagrammatic proof of Santos' inequality assumes a total absence of contextuality. This condition cannot be fulfilled for properties of the same particle that are assumed to be non-compatible. However, the inequality only contains measures of separation between properties of two different particles, and it will therefore be valid when the properties of particle 1 are independent of the context of measurement for particle 2 and vice versa.

The inequalities (B5) are identical with Bell's inequalities as derived by Clauser and Horne (Phys. Rev. D 10, 526 (1974)). For an experiment like Aspect's first<sup>22</sup>, where the a's and b's are the propositions that a photon has been detected through a polarizer of a certain setting, we can translate inequalities (B5) introducing the coincidence probabilities by the assumption  $p(a_i)=p(b_j)=\frac{1}{2}$ :

$$1 \geq p(a_1 \wedge a_2) + p(a_1 \wedge b_2) + p(b_1 \wedge a_2) - p(b_1 \wedge b_2) \geq 0. \quad (B7)$$

For example, if the four polarizer-orientations are chosen such that  $b_1$  and  $b_2$  are measured in the same direction, whereas the other three directions form angles of  $120^\circ$  to each other, we find from the right inequality of (B7), that the coincidence probability for two different directions should be greater than or equal to  $1/6$  (assuming that the coincidence probability is  $\frac{1}{2}$  for parallel polarizers). Quantum mechanics, on the other hand gives the precise value  $\frac{1}{2} \cdot \cos^2 120^\circ = 1/8$ , a value that is confirmed by the Aspect-experiment, so there can be no doubt that (B7) is violated. This case is identical with the case discussed in the popular exposition by Mermin (Physics Today, april 1985) who, however, seems to forget that the actual experiments are made by connected pieces of apparatus, and that all the so called violation of local realism lies within the violation of the inequalities (B7), which involves only coincidence countings. (See, however, Mermin's reply to comments, Physics Today, november 1985). The claim that the connections are irrelevant for the observed non-locality or contextuality is not well founded and can only be proven/disproven experimentally by doing the experiment without connections. The author's conjecture is that the inequalities will be satisfied for such an experiment.

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Projektrapport af: Per Hedegård Andersen, Lars Boye, Carsten Holst Jensen, Else Marie Pedersen og Erling Møller Pedersen.  
Vejleder: Jesper Larsen.
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Af: Mogens Niss.
- 109/85 "COX I STUDIETIDEN" - Cox's regressionsmodel anvendt på studenteroplysninger fra RUC.  
Projektrapport af: Mikael Wennerberg Johansen, Poul Katler og Torben J. Andreasen.  
Vejleder: Jørgen Larsen.
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Af: Bent Sørensen
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Fysiklærerforeningen, IMFUA, RUC.
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Projektrapport af: Jakob Heckscher, Søren Brønd, Andy Wierød.  
Vejledere: Jens Høyrup, Jørgen Vogelius, Jens Højgaard Jensen.
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Projektrapport af: Søren Brønd, Andy Wierød.  
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Paper presented at The International  
Workshop on Teaching Nonlinear Phenomena  
at Universities and Schools, "Chaos in  
Education". Balaton, Hungary, 26 April-2 May 1987.

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